Faculty of Engineering and Computing
Department of Civil Engineering

Variability in the Determination of Bulk and Maximum Density of Hot Mix Asphalt

Wilfredo Valenzuela

This thesis is presented for the Degree of
Master of Philosophy
of
Curtin University

October 2011

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge this thesis contains no material previously published by any other person except where due acknowledgment has been made.

Signature:………………………………………….

Date:………………………….............................

Variability in the Determination of Bulk and Maximum Density of Hot Mix Asphalt

ABSTRACT

Roads are a vital link, in particular in a country like Australia where distances are extensive. Western Australia is no exception, with Main Roads, Western Australia's State road authority, managing more than 17,800 kilometres of highways and state roads with a large local government road network of almost 164,000 kilometres (Main Roads Western Australia 2011). For quality control measures, Main Roads Western Australia (MRWA) requires quantification of the variability of test methods to establish accepted parameters, and minimum and maximum air voids for the construction of dense-graded hot mix asphalt concrete. This is done to ensure correct design and quality control of the pavement, and to avoid the prospect of distress that could affect the expected service-life of the hot mix. Western Australia currently uses the Marshall method for hot mix asphalt design which is proven in the production of quality hot mix asphalt and from which long lasting pavement can be constructed. This method has been in use around the world for over 60 years.

High quality and specific percentages of aggregates are then required for the durability and quality of the road. Therefore, the accuracy of the measurements of asphalt density hence the results are essential for the acceptance of the product. Payments are dependent on whether or not a certain asphalt density quality has been achieved. One form to measure this quality is by testing the volumetric properties of asphalt. However, it has been noticed in previous results that a high percentage of variability in the bulk and maximum density of the hot mix are present. This variability as a result have produced one of the major concerns in the asphalt hot mix industry, this is having a reliable density determination of compacted hot mix samples.

Consequently, this research aimed to examine the possible cause/s of the differences in density determination of dense-graded hot mix asphalt concrete. This translated into a thorough evaluation of previous test results, performed through proficiency and inter-laboratory testing. Investigation and evaluation of the current methods specifically focused on temperature testing and the testing and analysis of the possible causes of variability in the determination of bulk density. Extensive testing was conducted, using MRWA standard methods to measure asphalt density. This involved observing and replicating the methodology established for standard methods. There was a modification to the method for the determination of maximum density and this will be discussed in the report. These factors were considered to be crucial in order to make a significant contribution to promoting and improving standardisation across the industry, and to ensure reliability and consistency in the determination of asphalt density, both bulk and maximum.

ACKNOWLEDGEMENTS

This research is part of the study on The Variability of the Bulk and Maximum Density Determination in Hot Mix Asphalt. The study was carried out at BGC Laboratory and Curtin University. Many individuals and organisations have significantly contributed to the work during this study and I would like to gratefully acknowledge the contributions of the following individuals.

To the faculty members of the Civil Engineering Department at Curtin University, my supervisor Professor Hamid Nikraz, Dr. Peerapong Jitsangiam and Dr. Komsun Siripun, I wish to express my sincere gratitude for your kind and constant support, encouragement, and helpful advice and comments. In particular I wish to express my gratitude to Professor Colin Leek for his endless kindness, support and invaluable knowledge.

The goals of this project would not have been achieved without the support and kind help of BGC Laboratory Technicians, Mr. Jesus Ortiz and Alejandro Serrano for their assistance in performing laboratory experiments and their lively discussions. I would also like to thank Mr. Craig Hollingsworth, BGC Asphalt and Quarry General Manager for his support and for allowing me the time to do this research.

I am extremely indebted to my wife, Ingrid for her unconditional assistance, encouragement, wonderful support and most of all, patience and my friend Paul Connell for his continuous help with the English language. Finally, I wish to express my gratitude to my beautiful daughters Karina and Kathy for their continual encouragement and patience.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS/NOTATIONS

AAPA	=	Australian Asphalt Pavement Association
AC	=	Asphalt Concrete
AS	=	Australian Standard
DGA	=	Dense-graded Asphalt
HMA	=	Hot Mix Asphalt
M_1	=	Mass of Buchner flask in water in grams
M_2	=	Mass of test portion in air in grams
m_2	=	Mass of test specimen in water in grams
M_3	=	Mass of flask plus contents in water in grams
MRWA	=	Main Roads Western Australia
NATA	=	National Association of Testing Authorities, Australia
OGA	=	Open-graded Asphalt
P_{bulk}	=	Bulk Density of test specimen in t/ m^3
P_{max}	=	Maximum Density of the Asphalt in t/m^3
PT	=	Proficiency Testing
P_w	=	Density of water at 25^o C in t/ m^3
		Maximum density
P_w	=	Density of water at 25^o C in g/ cm^3
		Bulk density (sufficiently correct to use 0.997)

QA	=	Quality Assurance
QC	=	Quality Control
VFB	=	Voids Filled with Bitumen
VMA	=	Voids in Mineral Aggregates
V_{sample}	=	Volume of test specimen in cm^3

CHAPTER 1

INTRODUCTION

The aim of this chapter is to develop an understanding of the project and provide an overview of hot mix asphalt mixture, the manner in which the laboratory performs the compaction of sampling and the current methods used for the determination of hot mix asphalt density, in particular the bulk density.

The purpose of designing hot mix asphalt is to “determine the optimal proportions of bitumen and crushed aggregates required to produce asphalt” (Asphalt Mix Design Main Roads, 2011). That is, the asphalt should meet the set specifications and if it does so, then it is assumed to be a good and durable product. An essential aspect of the mix design is to ensure that the volumetric properties of the asphalt are fit for the purpose. Main Roads Western Australia (MRWA) and the Australian Asphalt Pavement Association (AAPA) have established standard specifications for volumetric properties in the design and construction of dense grade hot mix asphalt (HMA). Setting standards and specifications ensures quality control (as much as possible) and avoids and minimises the probability of the hot mix asphalt undergoing distress such as deformation, cracking and moisture-related damage. Any deviation from the specification could alter the service-life of the asphalt.

Currently, the standard specifications for density measurements for quality control (QC) and quality assurance (QA) are stipulated by Main Roads Western Australia

(MRWA) and the Australian Asphalt Pavement Association (AAPA). Testing to determine the bulk density is done using the Marshall Method, MRWA 7311(MRWA, 2011). The maximum density is determined using the MRWA Rice method 732.2 (MRWA, 2011) and for the end calculations of volumetric properties, method MRWA 733.1 is used (MRWA, 2010). The acceptance of the HMA pavement relies on the accuracy of the measurements, specifically the volumetric properties.

However, investigations and observations (ConLaps, Construction Laboratories Auditing and Proficiency Services, 2009) show that there is a high percentage of variability in the determination of asphalt density results (bulk and maximum density) which affect the calculation of air voids. Although a number of possible reasons could be identified as potential causes for the variability, the exact cause is unknown. Further, these observations have raised the question of the confidence placed in the standard methods to determine HMA density.

1.1 Background

Hot mix asphalt is widely used in the construction and surfacing of roads all over the world. Therefore, an optimal design mix is extremely important in order to achieve the best proportions to produce a workable and durable end product. Usually, towards the end of the life of the hot mix asphalt, maintenance costs increase so that roads can be kept in good structural condition. Maintenance or reconstruction of HMA roads requires time and work, and these in turn reduce traffic flow, often resulting in both traffic and construction delays.

A study by Scholz, (Scholz et al, 2002) stated that if the life of a pavement can be extended by two years before major reconstruction, a significant reduction in the whole of life cost is achieved, especially on higher volume roads. Therefore, the best way to avoid premature maintenance and reconstruction is to ensure the hot mix asphalt concrete is properly designed and constructed in the first place. Correctly designed mixtures and effective compaction are essential factors in determining the performance of dense-graded hot mix asphalt (HMA). The design method specified by Main Roads is the Marshall method of mix design, which determines, through a number of tests, the optimal combination of aggregates, filler and bitumen required to satisfy the specification.

It is well known that inadequate compaction results in pavement with decreased stiffness, decreased durability (early signs of ageing), decreased fatigue life and the increased possibility of rutting, ravelling and moisture damage. All of these factors decrease the life of HMA. The performance of HMA is strongly dependent on the mix design. In conclusion, an imperative part of the process is the determination of both the bulk and maximum densities of HMA.

It is essential to have accurate measurements of density to indisputably determine whether or not adequate compaction of HMA has been achieved. Inadequate density determination eventually results in having to repair or rehabilitate a pavement before it has reached the end of its design life. Accurate density measurement can detect inadequate proportions and allow for corrections. Significant whole of life cost savings, conservation of resources and the maximisation of the embedded energy are achieved by the achievement of the required asphalt density in dense-graded pavements, and this extends the design life of the pavement. In addition, uniformity of measurement may preclude disputes between practitioners.

1.2 Objectives

The main objective of this study was to make recommendations on, and minimise the variability that occurs when measuring the concrete density of dense-graded hot mix asphalt used in Western Australia and other states. By reaching these objectives, future quality control and quality assurance should be achievable. In order to produce the required outcomes it was necessary to:

- Study and analyse previous proficiency testing to determine and establish the variability found in dense-graded hot mix asphalt.

- Investigate and evaluate the efficiency of the current method/s used by MRWA and other agencies for determining HMA density.

- Determine the possible cause/s that produces the variability in both bulk and maximum densities.

- Conduct laboratory testing and analysis to determine the possible cause or causes of the variability in the determination of HMA density.

- Provide recommendations for changes to current method/s of use in order to improve accuracy and minimise the variability in HMA density determination and avoid premature road failure as well as disputes between practitioners.

The findings from this study will be used to develop recommendations for:

- Improving and minimising the variability in the bulk and maximum densities of asphalt

- Achieving consistency in the determination of asphalt density to prevent conflict between practitioners and their clients

- Contributing to the improvement of current practices, in order to standardise methods used.

1.3 Scope

The objectives of this research and the processes were carried out by using the following methodology as shown in figure 1.1.

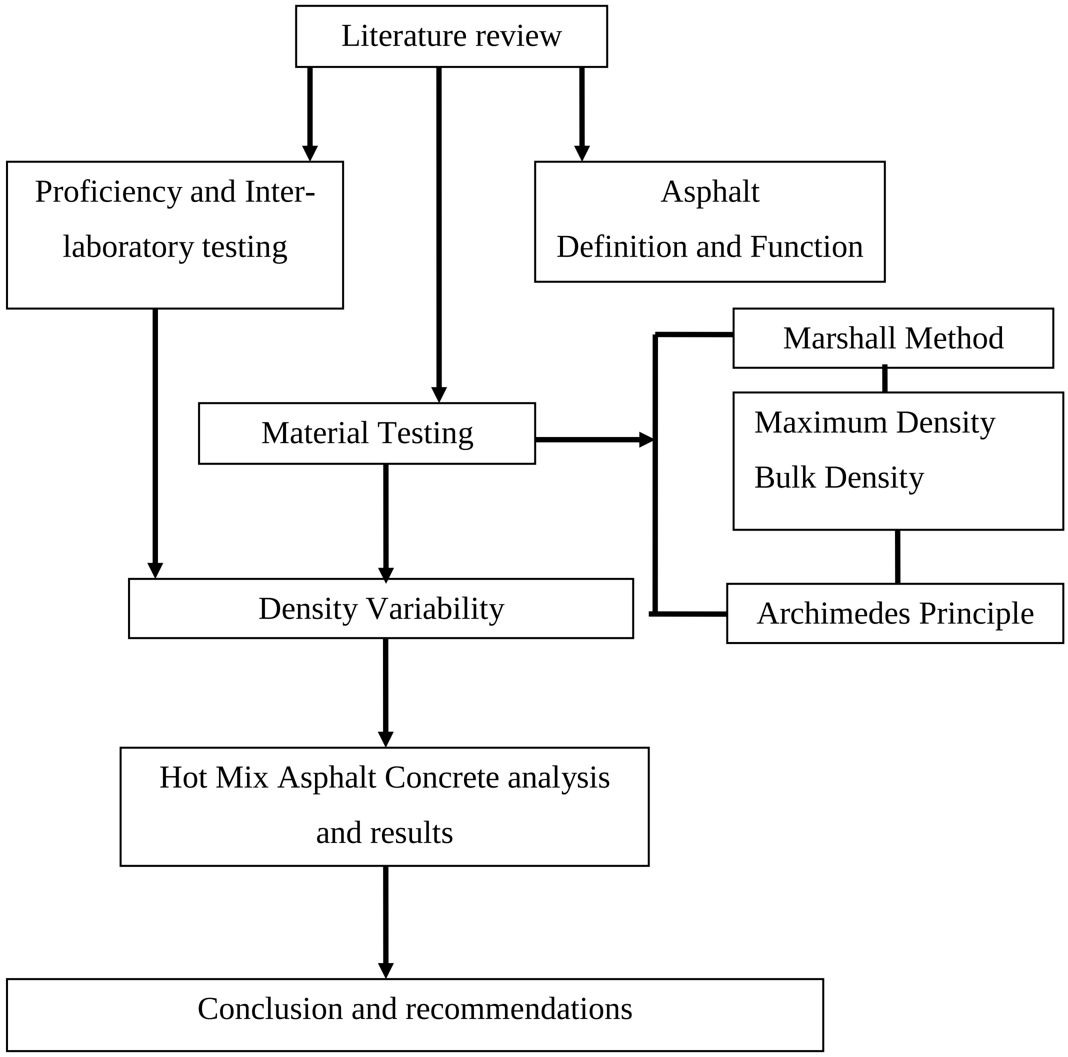

Figure 1.1 Diagram of study approach

CHAPTER 2

LITERATURE REVIEW

2.1 Definition and function of Hot Mix Asphalt Concrete

2.1.1 Hot mix asphalt concrete

Asphalt is the indispensable mixture that is primarily used for road construction; it must be carefully designed according to the needs of the road in question. Asphalt is also known as bituminous concrete. High quality and specific percentage aggregates are therefore required to ensure the durability and quality of the road. Density determination is a crucial process for asphalt quality control and sample testing is required to ensure that a high and consistent standard of asphalt quality is achieved and maintained.

Asphalt is a combination of mineral aggregates (coarse and fine), bitumen and filler. All of these elements are mixed together within a temperature range of approximately 140^{o} C to 170^{o} C to form a cohesive and fluid product (Aslab, n.d). Dense-graded asphalt (DGA) is a specific grading designed to maximise density and optimise the binder content to produce an economical mix. The mix is laid, while still hot, in a layer of 25 mm to 50 mm in thickness, on the surface of the road pavement either by hand or by using an asphalt paving machine. The mixture is then compacted with a vibrating steel drum and roller or multi-roller to form a uniform and well compacted/consolidated pavement surface. Lately, full depth asphalt has been implemented. It is a pavement in which asphalt is used for all courses above the sub-grade or improved sub-grade (CSR, 2008).

During the process of compaction, air is entrapped in the mixture in the form of voids between the coated aggregate particles. It is precisely this entrapped air that is of vital importance to the performance of the asphalt surface, which can undergo further densification under normal traffic conditions, and for the expansion of the bitumen in the hot weather. The aggregate grading, bitumen and filler contents and the volume of air voids are designed into the mix. The method most commonly used in Australia and around the world is the "Marshall Design Procedure".

2.1.2 Asphalt Types

Asphalt can be used for:

- The construction of new pavements
- The maintenance of an existing pavement (for the correction of surface irregularities, or to provide a new wearing surface or for strengthening the pavement).

There are a number of factors that need to be considered when selecting the appropriate asphalt type, such as the condition of the pavement, strengthening requirements, pavement design and surface characteristics. By considering these factors it is possible to select the type of asphalt mix, the layer thickness, the type of binder and aggregate as well as the nominal size of the mix.

The main types of asphalt are (Main Roads, 2011)

1. Dense-graded Asphalt (DGA)
2. Open-Graded Asphalt (OGA)
3. Stone Mastic Asphalt (SMA)
4. Fine Gap Graded (FGGA)
5. Ultra-Thin Asphalt Surfacing (UTA)

Asphalt types vary according to the specific purpose for which the asphalt has been designed. The primary division between mixes is in terms of particle size distribution. The variations are dependent on the percentage of aggregates used. The principal mix types of asphalt used in Australia are dense-graded (DGA) and open-graded (OGA) types (Asphalt Mix Design Main Roads, 2011). This research focuses on the design of dense-graded asphalt, which requires a uniform grading structure to maximise the intrinsic strength of the aggregate and to maintain the required air voids thereby meeting the specifications. Dense-graded asphalt mix has a continuous distribution of particle size and filler and a low design air void content, normally within the range of 3 to 7 percent. This type of mix provides the greatest load carrying capacity for structural layers. It minimises the possibility of interconnection of void space, hence impending the passage of air and moisture through the surface. Dense-graded mixes are usually spread and compacted while hot.

Open-graded asphalt is the other extreme and has been designed to encourage the passage of water to drain water from the pavement surface, reduce noise and spray generation. In this type of asphalt, the aggregate factor is devoid of “fines” to ensure large void spaces (Aslab, n.d). Wherever the surface water can be a safety issue, open-graded asphalt is normally overlayed on dense-graded asphalt for high-speed roads.

2.1.3 Compaction Concept

Compaction of asphalt in flexible pavement is a vital part of pavement engineering but a mix that is properly design is critical to achieving the require air voids which are highly dependent on the efficiency of compaction. It is important then to consider the degree of compaction when designing the mixture, as the compaction process causes the asphalt mix to be compressed and its volume reduced. The differences in compaction can influence the properties of asphalt. The density of the HMA increases and the air void content of the mix decreases; they are therefore inversely proportional to each other. The service-life of asphalt is considerably reduced when there is an increase in air voids. As a result, the durability of the asphalt mix is highly reliant on the level of compaction achieved. Specially regarding post compaction densification by traffic. For this reason a different number of blows are used. The number of blows during testing represents the pavement use. The Marshall method specifies that 35 blows are for lightly trafficked pavements, the 50 blows are for medium density pavements and the 75 blows are for heavy duty pavements to ensure that traffic compaction on heavy roads does not reduce voids to unstable degree.

2.1.3.1 Laboratory Compaction

One of the purposes of the laboratory compaction is to replicate the compaction achieved during construction of the pavement in the field. The method used by the laboratories is described in MRWA 731.1- 2010 where an automated Marshall Compaction hammer is utilised for testing. Following the preparation of the test, the specimen is placed in the pedestal of the hammer and it is compacted with 35, 50 or 75 blows (according to the purpose of the mix). The steel hammer falls freely from a height of 457 mm, then the specimen is inverted and the same number of blows is applied to the other side of the test specimen.

2.1.4 Component Materials

The quality of materials required to make good asphalt is extremely important. As mentioned previously, the materials for an asphalt mixture are mineral aggregates, filler and bitumen. Usually, the aggregates are defined as coarse aggregate, which corresponds to the portion that is retained on a 2.36 mm sieve, and fine aggregate which is the portion that passes a 2.36 mm sieve and is retained on a 0.075mm sieve (Aslab, n.d). Production Tolerance is shown in table 2.1

Particle Size Distribution AS Sieve Size (mm)	**Tolerances on Percentage By Mass Passing**
4.75 and larger	$\pm$ 7
2.36 and 1.18	$\pm$ 5
0.6 and 0.3	$\pm$ 4
0.150	$\pm$ 2.5
0.075	$\pm$ 1.5

Table 2.1 Production Tolerance

2.1.4.1 Aggregate

The suitability of aggregates for use in asphalt concrete is determined by grading, resistance to abrasion, soundness, cleanliness, internal friction and surface properties (Wallace & Martin, 1967). Sampling Aggregates shown in Figure 2.1

The aggregate and filler represent around 96% by weight and 85% by volume of an asphalt pavement (Australian Asphalt Pavement Association, 2007). It is logical then that the strength and durability of the product (mix) is directly linked to the aggregate used. Aggregates should be clean, durable and free of damaging material. Aggregates may be produced from crushed and screened quarry products, natural sands and gravels, manufactured aggregates and recycled materials (Australian Asphalt Pavement Association, 2007). The most common source of processed quarry aggregate is Igneous rock (it is formed from molten materials) and can also include basalt, dolerite, andesite, granite, schists, gneiss and quartzite. These can be also used as asphalt aggregates (Australian Asphalt Pavement Association, 2007). Natural sands and gravels can be crushed, screened, and washed or they can be obtained as untreated bank run or pit sand. Products can be specially manufactured for use as aggregates or they can be the by-products of an industrial process such as slag, and calcinated bauxite.

Aggregates from different quarries have different varying specific densities, thus they vary in the size and shape of their aggregate particles. Usually, crushed material is preferable to natural material because the fractured faces improve bonding and can offer better skid resistance. Aggregates are composed of rounded particles, for example, river gravels and some natural sands.

Figure 2.1 Sampling Aggregate

According to the AAPA, the properties of aggregates can be classified into two groups depending on the type of material used. One group includes toughness, soundness, density, porosity, surface texture, resistance to polishing and an affinity with bitumen. The other group is dependent on properties that can be partially controlled and these include shape, particle size distribution (grading) and cleanliness (silt, clay and organic matter content).

Differences in the properties of crushed aggregates influence the properties of the produced asphalt. Therefore, the mix design for one region should not be used in another where the properties of the aggregate vary. The suitability of aggregates for use in asphalt mixes can be evaluated by a series of tests that are stipulated in the Australian Standard AS 1141, *Method for sampling and testing aggregates.*

These tests are:

Flakiness Index – Flat or elongated particles tend to break during mixing or when lying. This issue can significantly change the structure of the asphalt (MRWA 216.1).

Los Angeles Abrasion - This procedure gives an indication of the amount of deterioration of the aggregate that can occur during the mixing and placing processes (MRWA 220.2).

Sodium Sulphate Soundness - This test allows for the determination of the aggregates resistance to weathering. The test measures the durability.

2.1.4.2 Filler

In asphalt, most fillers are derived from the fine aggregate and it is the filler that passes through a 0.075 mm sieve (Austroads, 2007). Filler includes rock dust derived from coarse and fine aggregate fractions and other materials, such as lime, Portland cement and kiln dust. In dense-graded mixes the proportion of filler is around 4% to 6% by mass of the aggregates (Austroads, 2007). The function of the filler is to maximise binder content and to add stiffness to the binder and stability to the mix. It also affects the voids in the total aggregate. Relevant filler requirements are available in AS 2150-2005 or relevant asphalt specifications. Generally a maximum of 3% moisture content applies to all filler materials.

In cases where natural filler is insufficient, an introduced material may be used, such as hydrated lime, with the benefit that it can stiffen the bitumen, giving stability to the mix. In WA, the most common filler is crushed rock.

2.1.4.3 Bitumen

Bitumen is the medium that holds the mix (aggregates) together. It is a high viscosity fluid that when heated, becomes fluid and coats the aggregate particles in a fine film. When bitumen cools it becomes more viscous until it forms an elastic solid. Usually bitumen is supplied in two viscosity types:

- 170 class: used for most general work where heavy traffic or high standing loads are not encountered.
- 320 class: used for heavy duty applications such as major roads or container terminals. (Austroads, 2007).

The main characteristics of bitumen are strong adhesion, water resistance, flexibility and ductility, durability or resistance to weathering and low toxicity. The quality of the bitumen has considerable relevance to the performance of asphalt pavement. Tests are carried out to determine the quality of the product. Just as important as the component materials are to good asphalt, so the proportion of the materials is equally important. A poor or bad design, regardless of the quality of the component materials, will produce poor asphalt. On the other hand, a good design, utilising second rate materials, has a good chance of producing a functional product.

2.2. Concept

One crucial factor in the design of the aggregate is the layer thickness, as this determines the size of the aggregates to be used. To maximise the course stability, usually the largest aggregate size possible should be used, as long as the thickness required is at least 2.5 times the aggregate size. Before commencing the design, it is important to determine the use of the asphalt. It is the Marshall Method that allows for the design of a large range of mixes with different sized aggregates. The information that could affect the design includes:

- Asphalt use
- Asphalt construction
- Traffic flow
- Course thickness

In order to optimise the aggregate grading, and bitumen content, nine mix test samples are used following the Marshall Method (MRWA, 2011).The refinement of the asphalt mix samples need to be collected that represent the grading designs and different bitumen contents trialled. The samples need to be tested to establish:

- Maximum density (Rice Method)
- Bulk density (Marshall Method)
- Air voids and V.M.A (Voids Mineral Aggregate)
- Stability and Flow

Specification MRWA 504 of Marshall Properties for Dense-graded Asphalt Nominal 5mm, 10mm and 14mm for DGA is shown in table 2.2.

Parameter	Min	Max
Marshall Stability	8.0kN	-
Marshall Flow	2.0mm	4.00mm
Air Voids (WA 733.1):		
Nominal 10mm	3.0%	6.0%
Nominal 10mm – Perth and Southern areas of the state	4.0%	6.0%
Nominal 10mm – Northern and Eastern areas of the state	4.0%	7.0%
Nominal 5mm	3.0%	5.0%
Nominal 14mm (Intersection Mix)	4.0%	7.0%
Voids in Mineral Aggregate:		
Nominal 10mm Laterite	15.0%	-
Nominal 10mm	15.0%	-
Nominal 5mm	16.0%	-
Nominal 14mm (Intersection Mix)	14.0%	-

Table 2.2 Marshall Properties – Dense-graded Asphalt

2.2.1 Volumetric Properties

One of the major concerns of the asphalt hot mix industry has been the proper determination of the bulk density of compacted hot mix specimens. This issue has become a major concern due to the increased use of coarse gradations. Density determination is the basis for volumetric calculations used during the field control, construction, and the hot mix design. During the design stage, volumetric properties such as air voids, which can be the air voids in mineral aggregates (VMA) or the air voids filled with bitumen (VFB) and the percentage of maximum density are used to evaluate the acceptability of mixes. It is widely accepted that these volumetric properties are useful in predicting hot-mix asphalt pavement performance (VMA as a design parameter in hot mix Asphalt, 2000, p. 24).

Density is one of the fundamental parameters in the construction and design of asphalt mixtures. It is the single most important factor that affects the durability of the HMA. A hot mix that is properly designed and compacted should contain enough air voids to ensure durability, safety and most importantly, quality, to avoid permeability of air and water. According to the type of road, the voids of any mixture can vary but it cannot be too low or too high.

The initial in-place air voids are determined by comparing the bulk density to the theoretical or maximum density, and the final percentage of in-place air voids is estimated by comparing the bulk density in the laboratory with the compacted product in the field.

The percentage of air voids in an asphalt concrete mixture is without doubt the single most important factor that affects the performance life of an asphalt pavement. The air voids are primarily controlled by asphalt content, followed by the compaction effort during construction and the additional compaction under traffic. The methods recommended for use in Australia are stipulated by Main Roads WA and Australian Standards. In simple terms, the density of a material is defined as the weight of the material which occupies a certain volume in space. The density of asphalt mix controls its durability.

2.2.1.1 Maximum Density

Maximum density of asphalt is determined by using the Rice method. The method is used for determining the maximum density of asphalt mixtures, which is one of the main test parameters used for mix design and construction quality control. It is used to calculate the percentage of air voids in compacted hot mix asphalt and provides target values for HMA compaction. The maximum density is the HMA density excluding air voids. Theoretically, if all the air voids were eliminated from a hot mix asphalt specimen, the combined density of the remaining aggregate and bitumen would be the maximum density, which is referred to as Rice density, after its inventor (method MRWA 732.2). Minimum Mass for Test Portion is shown in table 2.3.

Nominal Max Size of Asphalt (mm)	Minimum Test Portion Size (g)
20, 14	1.500
10, 7, 5	1.000

Table 2.3 Minimum Mass for Test Portion

Figure 2.2 Loose Asphalt Preparation for Maximum Density

To calculate the maximum density of the asphalt, the following formula is used:

$$P_{max} = \frac{M_2}{M_2 - (M_3 - M_1)} P_w \tag{1.1}$$

Where P_{max} = maximum density of the asphalt in t/m^2

P_w = density of water at 25^o C in t/m^3

M_1 = mass of Buchner flask in water in grams

M_2 = mass of test portion in air in grams

M_3 = mass of flask + contents in water in grams

2.2.1.2 Bulk Density

Bulk density method MRWA 733.1 is based on the surface dry saturated method. The method basically uses a compacted laboratory or field hot mix asphalt specimen. The bulk density is decisively one of hot mix asphalt's characteristics because it is used to calculate other parameters, such as air voids, voids in mineral aggregates (VMA) and maximum density. The dependence on bulk density is because the mix design is based on volume, which is indirectly determined using mass and specific gravity. Specimen measurement for bulk density is shown in figure 2.3.

Bulk density is calculated as follows:

$$\mathbf{P_{bulk}} = \frac{\mathbf{m_1}}{\mathbf{V_{sample}}} \tag{1.2}$$

Where

P_{bulk} = bulk density of test specimen in t/m^3

m_1 = mass of test specimen in grams

V_{sample} = volume of test specimen in cm^3

Figure 2.3 Specimen measurement for Bulk Density

2.2.1.3 Archimedes Principle

To understand the possible causes of potential errors in testing results, it is necessary to comprehend the principle of the water displacement method (Method MRWA 733.1- 2011). The method is based in the Archimedes Principle which states that when an object is completely submerged in a fluid, the volume of fluid level that rises equals the volume of the object.

The water displacement method uses the following formula to calculate the volume of the test specimen established in test method MRWA 733.1 – 2011.

$$V_{sample} = \frac{(m_1 - m_2)}{P_w}$$

Where

V_{sample} = volume of test specimen in cm^3

m_1 = mass of test specimen in air in grams

m_2 = mass of test specimen in water in grams

P_w = density of water at 25^o C in g/cm3 (sufficiently correct to use 0.997)

2.3 Density Parameters

The air voids in any asphalt mixture are directly related to density; therefore density should be controlled to ensure that the air voids stay within an acceptable range and fall under the pre-established requirements.

2.3.1 Temperature Effect

The main factor in the workability of HMA is the temperature during the compaction process. The temperature is influenced by placement temperature and the rate of cooling. The asphalt cooling rate is a combination of heat loss into the pavement base and the atmosphere (AAPA, 2010). There are a number of factors that can affect the temperature, being the lay-down temperature, the pavement temperature, the layer thickness and the wind speed.

Temperature is one of the most important factors affecting the cylindrical test specimen. It is essential that the temperature during testing of the specimen is monitored and controlled to within 140^{o}C.

CHAPTER 3

METHODOLOGY AND EXPERIMENTAL DESIGN

3.1 Overview

This chapter presents the study methodology and the experimental design trialled in this research. The main objective was to evaluate the temperature factor, which is part of the method used in Western Australia. The study was based on laboratory test results (both previous and those used during the research) to test the current effectiveness of the measurement of asphalt density, in particular the bulk density. The laboratory testing was divided into two key parts, specimen preparation and density determination. The major part of this study effort focuses on the temperature issue of the test specimens during the process, to determine the asphalt density. The DGA hot mix containing Perth aggregates was applied in this study. The mix was selected because of its frequent use in Western Australia. The research addresses specific issues concerning the density measurement of DGA using cylindrical specimens, and describes the procedures used to determine the optimal asphalt bulk density.

3.2 Experimental Design

The research describes the experimental design developed to assemble evidence to facilitate and improve the variability of asphalt density experienced in the industry at present. Firstly, previous proficiency and inter-laboratory testing were studied and analysed in order to establish the variability present in results of dense-graded asphalt hot mix concrete. Consequently, testing was conducted to determine whether the temperature factor is the part of the process that could be improved to minimise the variability. As soon as the experiment plan was completed, analysis of the laboratory results was carried out. Finally, the results were used for recommendations and conclusions were drawn.

3.3 Previous Testing

3.3.1 Proficiency Testing

The Proficiency testing (PT) function complements existing procedures adopted by facilities to assure the quality and evaluation of performance of the activities for which they are accredited or seek accreditation (National Association of Testing Authorities, Australia, NATA). In this case, proficiency testing is performed to see if the results obtained are within the average standards utilised by all relevant practitioners. Laboratory participation and performance in proficiency testing is reviewed by NATA at assessment. As established by NATA, all facilities are encouraged to participate in as broad a range of PT activities as practicable, at least once every two years (different frequencies may be stated in the various field policies). For all material testing, engineering laboratory proficiency testing is performed at least twice a year.

Proficiency testing results are shown in tables 3.1 and 3.2. They show the variability present in the testing results within the different laboratories. The test results are from the years 2007 to 2011. All proficiency testing is done following the established method for testing established by MRWA. The variability in the results confirms a range of between 5.8 and 4.5 of air voids of the same mix tested specimen. The variability demonstrates that there must be a factor producing such a range of density results which in turn results in conflict between the laboratories. In the end it becomes costly and time consuming, and most importantly the precision of the method cannot be quantified.

Laboratory Number

Method	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Max. Density	2.424	2.412	2.374	2.43	2.407	2.425	2.395
z scores	0.873	0.079	3.095	1.349	0.476	0.952	1.428
Bulk Density	2.284	2.289	2.264	**2.3**	2.271	2.293	2.288
z scores	0.300	0.075	1.799	0.899	1.274	0.375	0.000
Air voids	5.800	5.100	4.600	5.300	5.700	5.400	4.500
z scores	1.124	0.450	1.574	0.000	0.899	0.225	1.799
Marshall Flow	3.250	2.250	4.000	3.200	2.750	3.250	3.250
z scores	0.000	4.497	3.372	0.225	2,248	0.000	0,000
Marshall Density	12.3	8	13.1	9.9	11	13.6	7.4
z scores	0.379	1.433	0.717	0.632	0.169	0.927	1.686
V.M.A	18.9	18.2	16.8	18.2	18.2	18.6	16.9
z scores	1.574	0.000	3.148	0.000	0.000	0.899	2.923
V.F.B	69.5	71.9	72.3	70.7	68.8	70.7	73.7
z scores	0.899	0.899	1.199	0.000	1.424	0.000	2.248

Table 3.1 Proficiency Testing Results

Laboratory Number

Procedure	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Max. Density	2.448	2.441	2.443	2.454	2.456	2.462	2.459
z scores	0.809	1.754	1.484	0.000	0.270	1.079	0.674
Bulk Density	2.286	2.311	2.307	2.309	2.3	2.302	2.344
z scores	2.423	0.330	0.110	0.110	0.881	0.661	3.964
Air voids	6.600	5.300	5.600	5.900	6.300	6.500	4.700
z scores	1.176	0.623	0.208	0.208	0.761	1.038	1.453
Marshall Flow	2.750	3.500	3.000	3.500	3.750	2.750	3.250
z scores	1.499	0.300	0.899	0.300	0.899	1.499	0.300
Marshall Density	14.5	12.8	13.1	10.8	12.4	12.7	16.7
z scores	2.098	0.060	0.420	2.338	0.420	0.060	4.736
V.M.A	19.2	18.5	18	18.5	18.9	18.2	17.4
z scores	2.184	0.385	0.899	0.385	1.413	0.385	2.441
V.F.B	65.4	71.2	69.1	68	66.5	64.2	73.2
z scores	0.988	0.831	0.173	0.173	0.643	1.365	1.459

Table 3.2 Proficiency Testing Results

In table 3.3 it is possible to observe the inter laboratory quality control, its precision and variance in the Marshall method. It shows how it affects the compaction results that lead to a project/work classification of conformance or non-conformance. Laboratory number 2 shows that it is within the specifications while laboratory number 1 some of the results are not within the specifications.

	Laboratory 1				Laboratory 2			
Date Laid	Compaction (%)	Mat Voids (%)	Max D (t/m^3)	Bulk D (t/m^3)	Compaction (%)	Mat Voids (%)	Max D (t/m^3)	Bulk D (t/m^3)
29/10/2008	93.7	10.1	2.431	2.307	94.7	10.1	2.405	2.279
30/10/2008	92.2	13.4	2.439	2.288	94.5	10.5	2.408	2.278
27/11/2008	94.6	10.4	2.456	2.313	98.2	6.7	2.419	2.286
25/11/2008	93.6	8.7	2.392	2.329	97.3	6.4	2.382	2.293
2/12/2008	95.8	7.1	2.412	2.313	94.5	9.1	2.382	2.291
19/01/2009	96.4	6.5	2.414	2.340	98.2	5	2.387	2.308
29/01/2009	95.9	9.5	2.451	2.313	97.7	7.7	2.411	2.277
2/09/2010	95.5	7.4	2.384	2.310	97	6.3	2.359	2.280
30/09/2010	95.4	8.3	2.383	2.293	95.7	8.3	2.378	2.278
4/10/2010	96.8	7.4	2.401	2.298	95.8	7.9	2.386	2.295
25/10/2010	95.9	6.9	2.387	2.318	96.6	7.6	2.375	2.272
29/10/2010	96.6	7.7	2.392	2.284	99.2	5.2	2.367	2.261
28/10/2010	96.4	6.6	2.308	2.225	98.1	6.2	2.374	2.270
4/11/2010	96.5	8.4	2.393	2.271	97.4	6.5	2.389	2.293
23/11/2010	96.4	7.4	2.398	2.304	98.7	5.6	2.381	2.290
19/11/2010	96.1	7.3	2.395	2.311	97.5	6.2	2.494	2.407
25/01/2011	92.4	9.9	2.446	2.384	95.6	7.6	2.449	2.368
31/01/2011	96.2	6.2	2.471	2.409	97.7	6	2.453	2.359
16/01/2011	99.7	2.2	2.485	2.438	99.8	3.7	2.494	2.407
18/01/2011	97.6	4.4	2.472	2.421	98.5	5.6	2.479	2.377
23/01/2011	95.4	8.4	2.563	2.460	98.5	6.1	2.545	2.428
4/07/2011	93.9	10.2	2.475	2.380	94.8	9.3	2.465	2.358
29/06/2011	95.4	9.7	2.508	2.385	96	8.6	2.479	2.37
27/06/2011	91.8	11.1	2.515	2.436	95.3	9.3	2.485	2.364

Table 3.3 Inter Laboratory Quality Control Results

3.4 Main Materials in this Study

3.4.1 Dense-graded Asphalt

During the entirety of the study, only the DGA was used. It is a compacted layer of mix wearing course that needs to withstand the shearing action caused by the acceleration, braking and turning of heavy vehicles without appreciable displacement (Dickinson, 1984).

The strength of the mix is obtained by producing an interlocking structure of the aggregate particles held together by thin films of binder between the particles. The mix is produced by having a high density (low air voids content) in the layer. The strength is also dependent on the size of the aggregate particles used in relation to the thickness. General purpose wearing course in light and medium traffic applications with a nominal size of 10mm usually have a typical layer thickness between 25-40mm (AAPA, 2004).

3.5 Specimen Sampling

Sampling is carried out for quality control and/or mix design evaluation. For this study, each specimen was taken from the same batch of dense-graded asphalt hot mix production. The study followed the procedure obtained from AS 2891.1.1-2008. Sampling asphalt was performed using materials removed from a truck by hand (figure 3.1).

Sampling Procedure

Method procedure was performed as follows:

a) At least three sample sites were selected.

b) At least 80 mm thickness of asphalt was removed (300mm wide and 200mm deep).

c) A vertical face cut was made through the horizontal bench.

d) A sampling tool was inserted into the vertical face of the exposed bench and the tool was withdrawn without spilling the contents.

e) The sample increment was placed in a sampler container without loss of asphalt.

f) All the sample increments were then combined to form a bulk sample.

g) Each bulk sample was then placed in a separate sample container and recorded and identified.

Figure 3.1 Asphalt Sampling

3.5.1 Preparation of Test Portions

Special care needs to be taken when preparing the samples, to avoid segregation and to minimise the loss of temperature, which is particularly important with regard to moisture loss and volatile oils (AS 2891.1.1). Preparation was performed as follows:

a) The bulk sample was broken into small pieces, without removing the binder coating on the aggregate or breaking the aggregate particles.
b) The bulk sample was placed on a quartering tray (figure 3.2)
c) The bulk sample was then thoroughly mix and formed into a cone by heaping.
d) The cone was flattened and divided into quarters with a quartering tool. Special care was taken to avoid segregation of the mix.
e) Each of the diagonally opposite quarters from the tray was separated to give two sub-samples.
f) Each of the two quarters was remixed by taking full scoops alternately from each quarter and placing them on the centre of the plate to form a cone.
g) The above steps were repeated until the combined mass of the two diagonally opposite quarters remaining was of a test portion size.

Figure 3.2 Sampling quartering

3.6 Compaction

Equipment necessary for compaction:

a) Marshall compaction mould assembly (complying with AS 2891.5).
b) Automated Marshall Compaction hammer, essential dimensions complying with AS 2891.5. Compaction Hammer Specifications is shown in table 3.4.
c) Balance of at least 2 kg capacity.
d) Digital PT100 thermometer.

APPARATUS	VALUE	WORKING TOLERANCE
HAMMER		
Mass.kg	4.535	$\pm$ / - 0.02
Drop Height mm	457	$\pm$ / - 1.0
Food diameter mm	98.5	$\pm$ / - 0.5

Table 3.4 Compaction Hammer Specifications

Note: All equipment complied with all required specifications.

Figure 3.3 Compaction Hammer

Compaction was carried out as follows:

a) For compaction, the mould (base and extension collar) was placed in the oven for at least one hour.

Test specimen required temperatures is shown in table 3.5

Asphalt Type	Dense Graded		Open Graded	
Bitumen Class	Class 170	Class 320	Class 170	Class 320
Temperature C^o	140 $\pm$ 5	150 $\pm$ 5	115 $\pm$ 5	125 $\pm$ 5

Table 3.5 Test Specimen required temperature

b) Mould was removed from the oven and a paper disc was placed into the mould.

c) A single test portion was placed into the mould (normally a mass of between 1200g and 1250g is required). A paper disc was then positioned on the surface of the material in the mould and a thermometer was inserted into the centre of the mould.

d) The temperature of the test portion was recorded. If the temperature had not reached its ideal, according to table 3.5, the mould and test portion were placed back into the oven. Otherwise the mould and test portion were left to cool down until reaching the desired temperature

e) The thermometer was removed. The mould and test portion were placed into position on the compaction pedestal (Figure 3.3). The specimen is compacted according to mix on one side. The mould then was inverted and the same number of blows was applied to the other end of the test portion. Note that the number of blows varied according to the mix specifications

f) The mould was given an identification number.

g) The mould and test specimen were left to cool down in air to avoid deformation when removing.

h) The specimen is then removed from the mould and it is ready for testing.

3.7Calculations

3.7.1 Bulk Density

Determination of bulk density is done by using the water displacement method. The procedure was performed as follows:

1. Determination of mass of the test specimen to the nearest 0.1g (m_1).

2. Determination of mass of the same test specimen to the nearest 0.1g but immersed in a water bath at 25^o C with an overflow device for maintaining a constant water level (m_2).

3. The formula was used to determine the specimen's volume.

$$V_{sample} = \frac{(m_1 - m_2)}{P_w}$$

4. Determination of the specimen density. Bulk density requires testing to be carried out to the nearest 0.001 t/m^3. The formula for bulk density determination is as follows.

$$P_{bulk} = \frac{m_1}{V_{sample}}$$

3.7.2 Maximum Density

To determine the maximum density, the Rice Method is used. This method determines the maximum density of the asphalt mix in the loose state, free from occluded air water displacement.

1. A test sample was obtained in accordance with Test method MRWA 701.12. Minimum mass for test portion is shown in table 2.3.

2. The particles of the test portion manually separate so that no aggregations of fine particles were larger than approximately 5 mm. Using sample division obtain a test portion from the test sample.

3. Mass was recorded to the nearest 0.1g and the flask was immersed in water (M_1) at 25 $\pm$ 1.0^o C.

4. The flask was partially filled with water from the bath to cover the sample. Approximately 2ml of detergent was added to the water.

5. The test portion was placed into the flask and the mass recorded to the nearest 0.1g (M_2).

6. The flask was stoppered and connected to a vacuum pump to remove the entrapped air of at least 90kPa, for 20 minutes (Vacuum removing air bubbles shown in figure 3.4).

7. The flask was agitated to help with the removal of air bubbles.

8. The flask was disconnected from the vacuum and submerged into a temperature controlled water bath (ensuring the sample was covered with water at all times to avoid introducing air).

9. The mass of the flask was recorded to the nearest 0.1g (M_3) and the test portion put underwater.

10. Determination of the specimen's maximum density was carried out to the nearest 0.001 t/m^3.

$$P_{max} = \frac{M_2}{M_2 - (M_3 - M_1)} P_w$$

Figure 3.4 Vacuum removing air bubbles

CHAPTER 4

DATA ANALYSIS AND RESULTS

This chapter presents the results of all the testing performed on dense-graded hot mix asphalt to determine the density (both maximum and bulk), closely following the methodology and experimental plan explained in Chapter 3. Firstly, all the data was consolidated into 6 tables and 6 graphs. From all the data gathered during testing, the maximum density and bulk density were calculated and tabulated. This data was performed and analysed in accordance with the MRWA standard for laboratory testing methods to determine the density of hot mix asphalt concrete.

The data and results exposed the variability established previously, as well as the minimisation of the variability when the methodology was followed, but the factor temperature was controlled in relation to bulk density testing (Appendix C Modified Bulk Density Method). Regarding the determination of maximum density, considering that the variability results did not show a highly disproportionate range in this study, the method was standardised to observe if any changes in results could be achieved. It should be noted that step 7 was modified in order to improve the results; no agitation was performed and the time was set at a precise 20 minutes (Appendix D Modified Rice Method).

Once all the data from this study was analysed, selected data from proficiency testing (PT) and inter-laboratory test results were compared to the data from this study. Finally, all the results of the density determination were gathered and evaluated to find correlations between the different tests.

4.1 Preliminary Data

In Chapter 3, proficiency testing and inter-laboratory results for asphalt density were demonstrated the variability between different laboratories and throughout the years. In tables 3.1 and 3.2 it is possible to observe the bulk density variability for the same test portion.

Both Proficiency Testing and Inter-laboratory testing demonstrate a high variability range in density results which affects the air voids. Test results in Proficiency testing show a variability range between 4.7 and 6.6 while in the Inter-laboratory testing results the range was between 2.1 and 4.1. The variability is also reflected in the mat voids were the range was between 13.4 and 10.5.

It is these differences that established the basis of this study. The factor temperature was considered to be the one element of the methodology that, if controlled at all times, could be decisive in the reduction of the asphalt bulk density variability. The maximum density also showed some variability. Therefore, there were factors affecting the variability which will be discussed later in the chapter. The combined variability is reflected in “the air voids percentage and compaction”.

4.2 Scope of Testing

All testing was performed using dense-graded hot mix asphalt from the same batch, and sampling was undertaken using the same number of test portions for each of the different type of dense-graded mixes. All the testing during the study followed the same protocol.

4.2.1 Density Testing of Asphalt Production – Round 1

The first set of testing was performed using hot mix from a daily production works of 450 tonnes of AC 7/ 35 (AC 7 stands for the type of mix and 35 is the number of compaction blows at testing). During the day, sufficient material was obtained for the 36 specimens to be tested. Samples were divided into lots of 12 specimens. Of each of the 12 specimens, 6 were tested by non-reheating and 6 by reheating (Dense graded asphalt specimens shown in figure 4.1). The specimens were tested as follows:

- 12 samples were taken from the first 50 tonnes of the mix.
- 12 samples were then taken from 180 tonnes production of the mix
- 12 samples were taken from the 350 tonne production of the mix.

Figure 4.1 Dense-graded Asphalt specimens

Table 4.1 shows all thirty six non-reheated and reheated tested specimens and the results obtained for bulk density. The first 6 specimens were tested by cooling the specimens at room temperature until the desired temperatures were obtained which were $140^{o}C \pm 5^{o}C$. The temperature was taken following the established procedure of the methodology. At that point it was noted that measuring the temperature using only one thermometer did not provide a comprehensive measurement as the temperature was only taken at the top level of the specimen. Within the rest of the mould test portion, the temperature was varied due to the outside of the mix cooling more rapidly than the inside.

Numbers of Specimens	Bulk Density t/m^3 Non Reheated	Bulk Density t/m^3 Reheated
1	2.315	2.338
2	2.295	2.325
3	2.317	2.337
4	2.300	2.330
5	2.275	2.329
6	2.262	2.328
7	2.309	2.335
8	2.301	2.340
9	2.269	2.334
10	2.259	2.336
11	2.270	2.331
12	2.307	2.329
13	2.314	2.340
14	2.326	2.333
15	2.277	2.327
16	2.269	2.341
17	2.266	2.338
18	2.257	2.329
Average	**2.288**	**2.333**
Standard Deviation	**0.023**	**0.005**
Minimum	**2.257**	**2.325**
Maximum	**2.326**	**2.341**
Variance	**0.00054**	**0.00003**

Table 4.1 Bulk density variability of non-reheated and reheated specimens (AC 7/ 35)

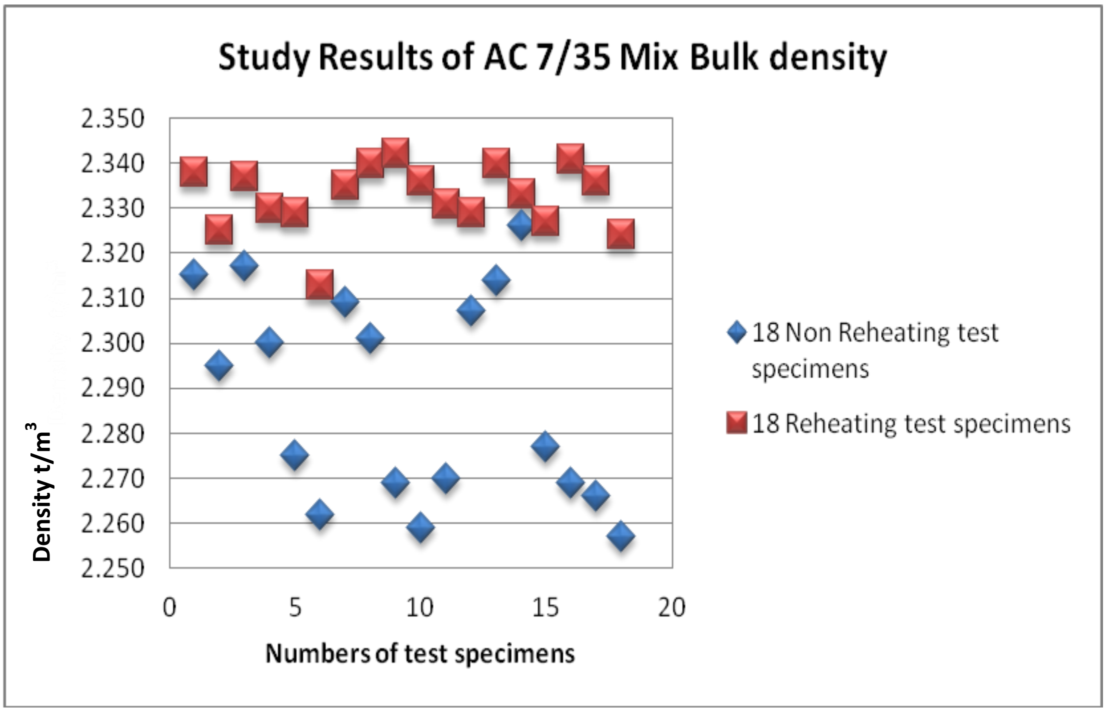

Figure 4.2 Non-reheated and reheated Specimens test results

The results of the bulk density for AC 7/ 35 show how the variability differs between the non-heated and reheated specimens. The reheated specimen results clearly show the minimisation of the variability and higher density. All the results and statistics were tabulated and are shown in table 4.1. It is possible to observe that the standard deviation as well as the variance decrease significantly when the specimen is reheated.

According to the results from the statistic tests, it is possible then, to conclude that the variability can be reduced and a higher density can be obtained by reheating the specimen.

Figure 4.3 Specimen Temperature

Figure 4.4 Specimen Temperature

Figures 4.3 and 4.4 illustrate the temperature differences within the same specimen. Figure 4.3 of the specimens show that one side had a low temperature of 127.8^{0}C that did not comply with the test standard, whilst the other side of the mould had a temperature of 135.6^{0}C within the temperature range required.

Figure 4.4 shows that the temperature on one side at 152.3^{0}C exceeded the required range whilst the other side at 137.0^{0}C fell within the range. Consequently, the subsequent test specimens were reheated to achieve a uniform temperature mix.

4.2.2 Density Testing of Asphalt Production - Round 2

The second lot of testing was performed using hot mix from a daily production works of a 350 tonne production of AC 10/ 50. During the day, sufficient material was obtained for 36 specimens to be tested. Samples were divided into lots of 12 and then subdivided into lots of 6 (6 non-reheated and 6 reheated). The specimens were tested as follows:

- 12 samples were taken from the first 50 tonnes of the mix
- 12 samples were then taken from 180 tonnes of the mix
- 12 samples were taken from 250 tonnes of the mix.

Numbers of Specimens	Bulk Density t/m^3 Non Reheated	Bulk Density t/m^3 Reheated
1	2.269	2.345
2	2.294	2.340
3	2.313	2.342
4	2.301	2.344
5	2.33	2.333
6	2.294	2.340
7	2.318	2.349
8	2.299	2.344
9	2.293	2.340
10	2.305	2.347
11	2.306	2.351
12	2.310	2.338
13	2.309	2.339
14	2.284	2.347
15	2.302	2.348
16	2.301	2.332
17	2.310	2.337
18	2.340	2.335
Average	**2.304**	**2.342**
Standard Deviation	**0.016**	**0.006**
Minimum	**2.269**	**2.332**
Maximum	**2.340**	**2.351**
Variance	**0.00026**	**0.00003**

Table 4.2 Bulk density variability of non-reheated and reheated specimens (AC 10/ 50)

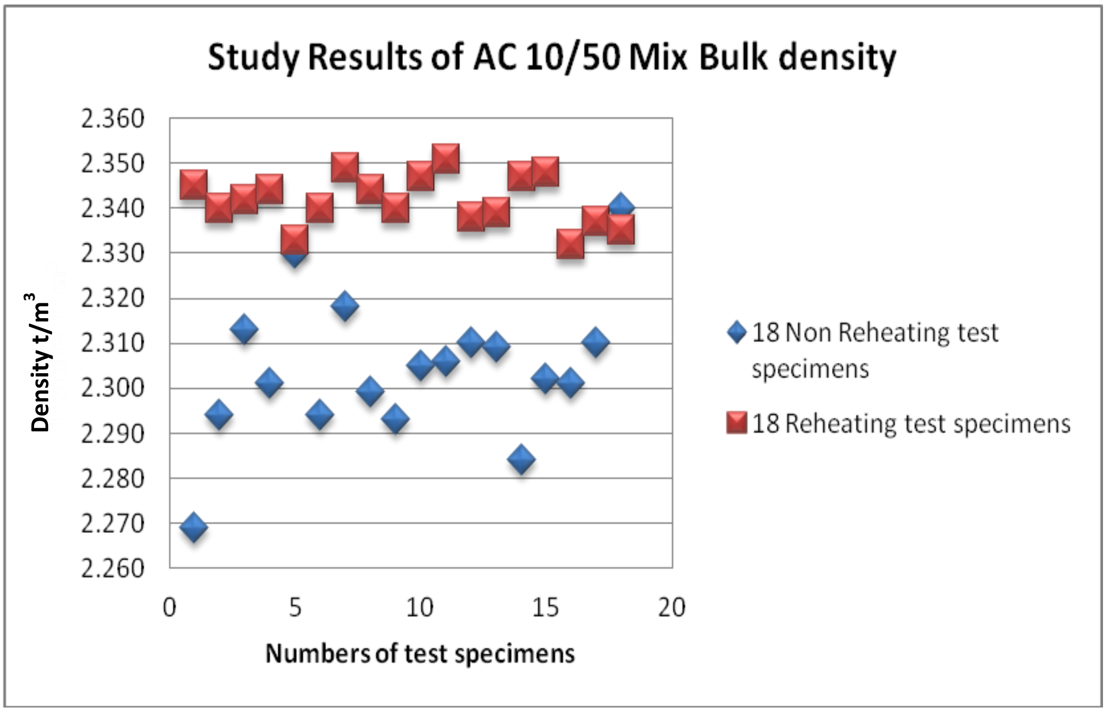

Figure 4.5 Non-heated and reheated specimens test results

In Figure 4.5 it is possible to observe that by reheating the specimen (1 hour in the oven at 145°C to achieve a uniform temperature of 140°C throughout the entire mould and test portion) the importance of the temperature factor when testing. The significance of the temperature factor in the results is the consistency that can be obtained.

4.2.3 Density Testing of Asphalt Production – Round 3

The third and final testing was performed using hot mix asphalt from a daily production works of 500 tonnes of AC 14/ 75. During the day sufficient material was obtained for 36 specimens to be tested. Specimens were divided into lots of 12 and then subdivided into lots of 6 (6 non- reheated and 6 reheated). The specimens were tested as follows:

- 12 samples were taken from the first 50 tonnes of the mix.
- 12 samples were then taken from 180 tonnes of the mix
- 12 samples were taken from 400 tonnes of the mix.

Numbers of Specimens	Bulk Density t/m^3 Non Reheated	Bulk Density t/m^3 Reheated
1	2.368	2.365
2	2.359	2.363
3	2.355	2.378
4	2.362	2.370
5	2.357	2.369
6	2.358	2.371
7	2.369	2.366
8	2.365	2.372
9	2.364	2.361
10	2.357	2.369
11	2.366	2.373
12	2.367	2.366
13	2.360	2.374
14	2.378	2.377
15	2.368	2.360
16	2.373	2.369
17	2.367	2.371
18	2.358	2.365
Average	**2.364**	**2.369**
Standard Deviation	**0.006**	**0.005**
Minimum	**2.355**	**2.360**
Maximum	**2.378**	**2.378**
Variance	**0.00004**	**0.00003**

Table 4.3 Bulk density variability of non-reheated and reheated specimens (AC 14/75

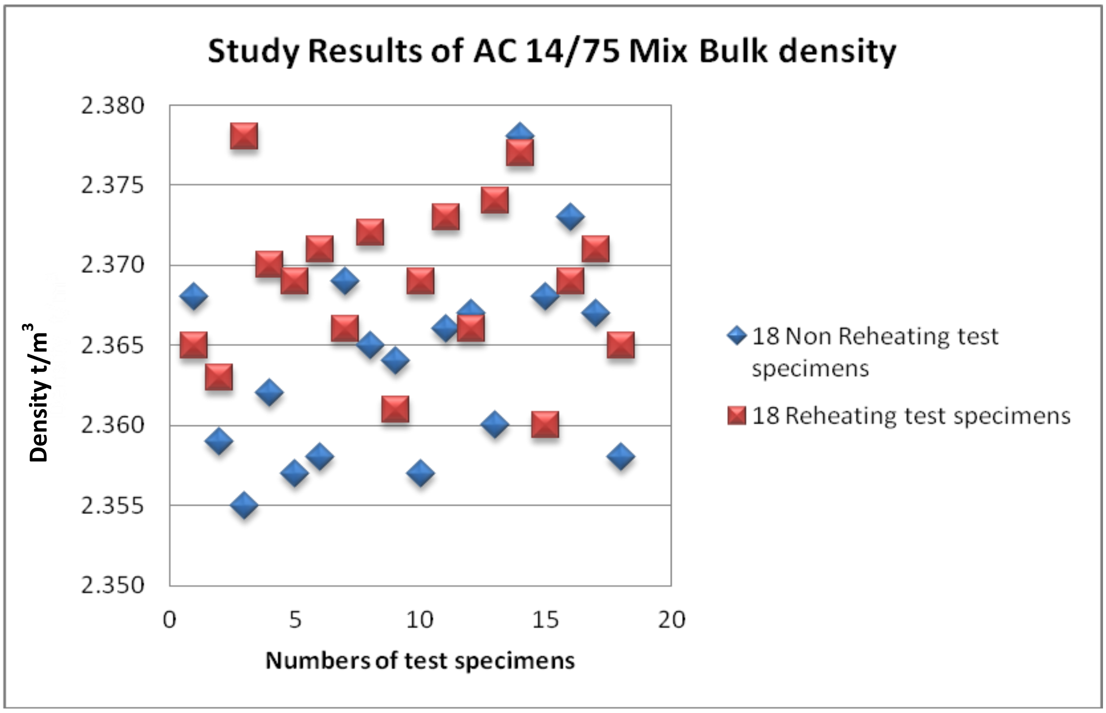

Figure 4.6 Non-reheated and reheated specimens test results

The results of the bulk density testing of AC 14/ 75 (Figure 4.6) which shows that the variability between the two studies is less, and this may be attributed to the fact that the cooling rate of the 14mm mix is lower, because bigger size rocks hold the temperature for a longer period. Therefore, heat dissipation is more constant throughout the mix. The results however still indicate a higher density in the reheated specimens.

4.2.4 Comments on bulk density test results

It is apparent from the test results that the reheating of the asphalt samples improves the consistency of the bulk density test results. As the reporting of field density is determined by the ratio of the density of cores taken in the field to that determined in the laboratory, and apparently variations in bulk density can significantly affect the ratio, the importance of obtaining an accurate bulk density cannot be overstated, particularly as this may reflect in reduced payment or rejection on the completed surface. Reviewing the data from the entire test results, previous and post-study, the evidence undoubtedly shows that the test temperature is the main factor affecting variability and density. This is particularly the case in mixes of 7mm and 10mm.

4.3 Maximum Density

4.3.1 Scope of Testing

All testing was performed using dense-graded hot mix asphalt from the same production, and sampling the same number of test portions for each of the different types of dense-graded mixes (AC 7/ 35, AC 10/ 50 and AC 14/ 75). All the testing during the study followed the same protocols.

4.3.2 Testing Asphalt Production- Round 1

The first set of testing was performed using hot mix from a daily production work of 400 tonnes of AC 7/ 35. During the day, sufficient material was obtained for 30 specimens to be tested. Samples were divided in lots of 10 specimens. Of those 10 specimens, 5 followed the MRWA method. The other 5 underwent a restructure of the procedure with the exception of step number 7 where the flask was not agitated periodically but only after 20 minutes exactly. It was then disconnected from the vacuum. The specimens were tested as follows:

- 10 samples were taken from the first 50 tonnes of the mix.
- 10 samples were then taken from 160 tonnes of the mix
- 10 samples were taken from 320 tonnes of the mix.

Number of Specimens	Maximum Density (t/m^3) Standard	Maximum Density (t/m^3) Non Standard
1	2.383	2.388
2	2.378	2.390
3	2.381	2.392
4	2.386	2.391
5	2.376	2.389
6	2.382	2.390
7	2.384	2.387
8	2.381	2.385
9	2.381	2.382
10	2.388	2.388
11	2.378	2.391
12	2.379	2.389
13	2.375	2.390
14	2.385	2.388
15	2.377	2.391
Average	**2.381**	**2.389**
Standard Deviation	**0.004**	**0.003**
Minimum	**2.375**	**2.382**
Maximum	**2.388**	**2.392**
Variance	**0.00001**	**0.00001**

Table 4.4 Maximum Density Results AC 7/ 35 (MRWA 732.2) (Standard and Non standard procedure)

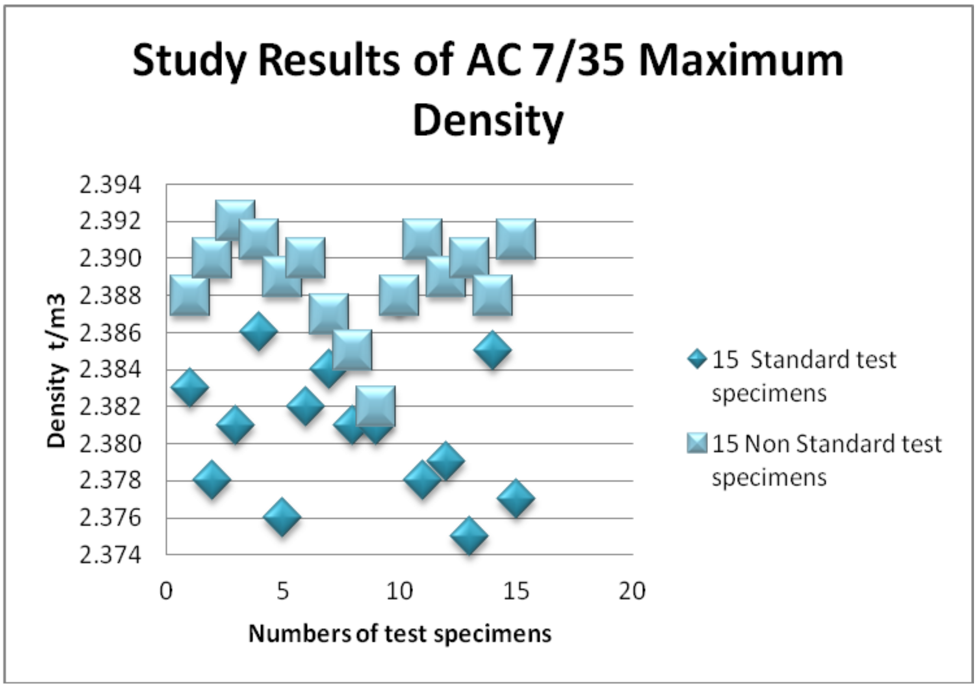

Figure 4.7 Maximum Density Variability Results

Figure 4.7 clearly demonstrates that with the non standard method it is possible to achieve a higher and more consistent density.

4.3.3 Testing Asphalt Production- Round 2

The second lot of testing was performed using hot mix from a daily production works of 300 tonnes of AC 10/ 50. During the day, sufficient material was obtained for 30 specimens to be tested. Samples were divided into lots of 10 specimens. The specimens were tested as follows:

- 10 samples were taken from the first 50 tonnes of the mix.
- 10 samples were then taken from 160 tonnes of the mix
- 10 samples were taken from 220 tonnes of the mix.

Number of Specimens	Maximum Density (t/m^3) Standard	Maximum Density (t/m^3) Non Standard
1	2.450	2.462
2	2.455	2.461
3	2.447	2.459
4	2.453	2.456
5	2.449	2.462
6	2.451	2.461
7	2.453	2.460
8	2.447	2.461
9	2.442	2.463
10	2.439	2.465
11	2.446	2.463
12	2.447	2.466
13	2.450	2.457
14	2.444	2.460
15	2.448	2.458
Average	2.448	2.461
Standard Deviation	0.004	0.003
Minimum	2.439	2.456
Maximum	2.455	2.466
Variance	0.00002	0.00001

Table 4.5 Maximum Density Results AC 10/ 50 (MRWA 732.2) (Standard and Non standard procedure)

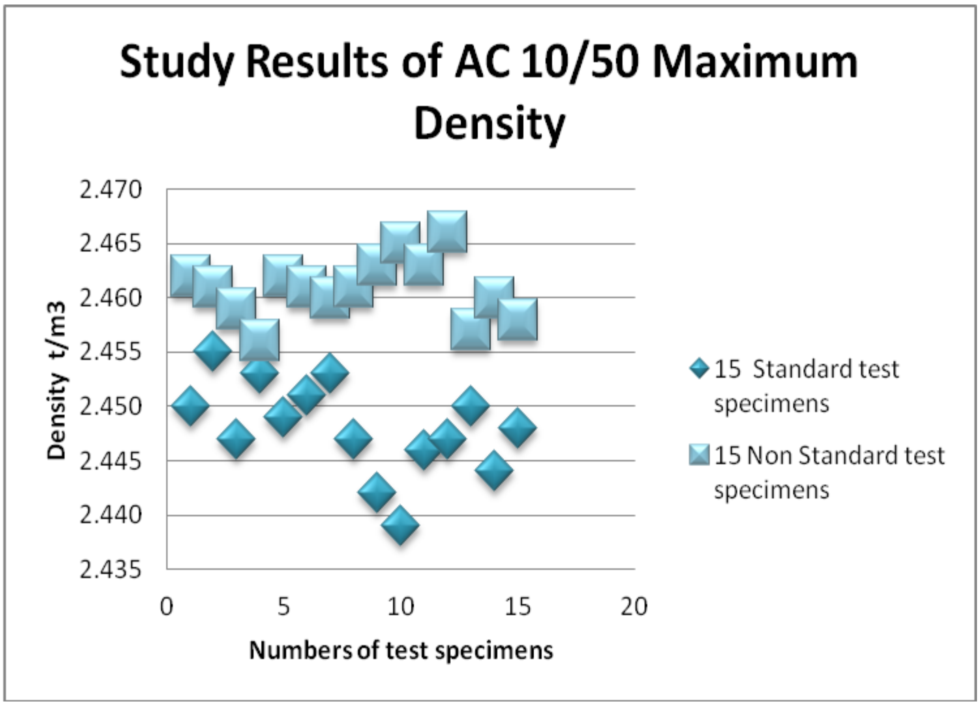

Figure 4.8 Maximum Density Results

The results of AC 10/50 shown in Figure 4.8 clearly demonstrate that the non-standard method achieves a higher and consistent density than the standard method.

4.3.4 Testing Asphalt Production- Round 3

The third and final testing was performed using hot mix asphalt from a daily production work of 450 tonnes of AC 14/ 75. During the day sufficient material was obtained for 30 specimens to be tested

Number of Specimens	Maximum Density (t/m^3) Standard	Maximum Density (t/m^3) Non Standard
1	2.470	2.493
2	2.476	2.498
3	2.480	2.495
4	2.475	2.499
5	2.479	2.493
6	2.471	2.491
7	2.478	2.489
8	2.480	2.493
9	2.476	2.498
10	2.469	2.495
11	2.473	2.490
12	2.468	2.493
13	2.469	2.488
14	2.473	2.493
15	2.479	2.496
Average	2.474	2.494
Standard Deviation	0.004	0.003
Minimum	2.468	2.488
Maximum	2.480	2.499
Variance	0.00002	0.00001

Table 4.6 Maximum Density Results AC 14/ 75 (MRWA 732.2) (Standard and Non standard procedure)

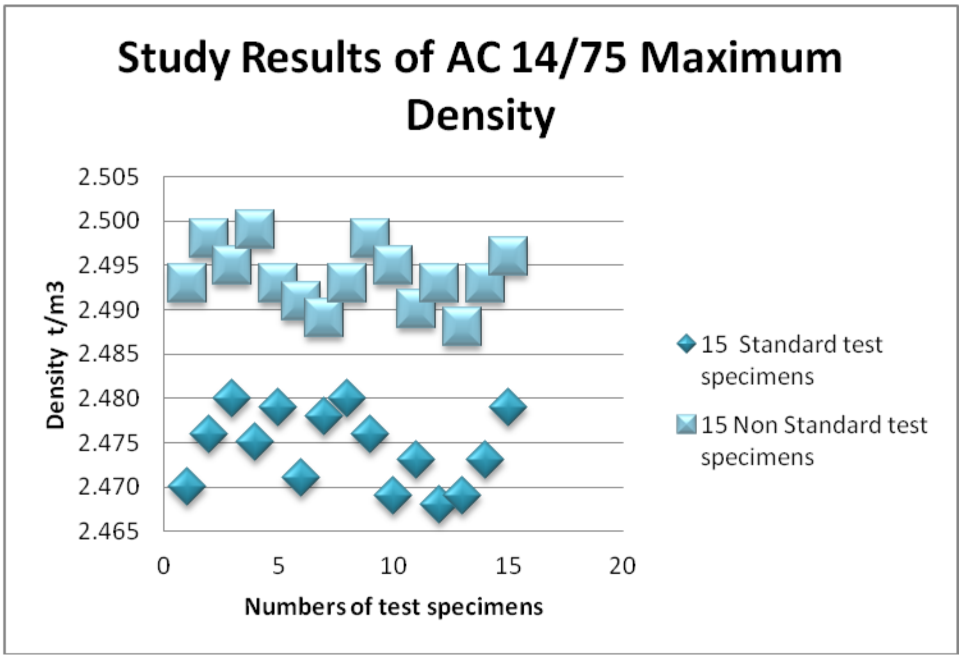

Figure 4.9 Maximum Density Variability Results

4.3.5 Comments on Maximum Density Testing

All the results from the different types of mixes display variability and although it is not significant in some samples, it can be concluded that the method in itself is not at issue regarding the variability. However, there are other factors that could contribute to the deviation of the results. It could be that the mix material composition was changed. It is possible to minimise the variability of the results by modifying the standard methodology process. In particular, step seven, which states “Agitate the flask and contents periodically to assist with the removal of air bubbles” (MRWA 732.2). The step was modified for this study and the agitation process was excluded on some occasions and on others was not agitated periodically, but rather after 20 minutes precisely. It is believed that agitating the flask and contents does not alter the number of air bubbles present in the specimen, and this is considering that the results followed both the standard method and the modified one. The non standard method gave higher density in all cases (results shown in Figures 4.7, 4.8 and 4.9)

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The overall objective of this study was to evaluate the density determinations, both bulk and maximum, of hot mix asphalt. A number of samples of dense-graded hot mix asphalt were extensively tested in the laboratory to determine the bulk and maximum densities. Based on the tests results of this study, the following conclusions are drawn.

5.1.1 Bulk Density

The findings for bulk density determination are:

1) Analysis of the tests results for the determination of bulk density demonstrates that an important issue, at the moment of testing, is the temperature. The bulk density determination is directly linked to the uneven temperature found in the specimens.

   Temperature is the basic element on which the compaction process is based. If the temperature at the moment of testing is not uniform, the results will show a high variability.

2) The previously mentioned issue can be overcome by reheating the test specimen at a constant oven temperature of 145^{o} C for at least one hour. After an hour the specimen reaches the required temperature and a consistent temperature. Low variability can therefore be achieved and consequently it is possible to obtain a consistent density value.

3) Based on the results from this study, an improved method in relation to temperature settings can be created and meaningful acceptance parameters can be drawn.

4) Using the appropriate equipment, qualified and experienced technicians and an improved method gives more reliable and accurate results which will effectively influence quality control and the mix design.

5.1.2 Maximum Density

The findings for maximum density determination are:

1) The data from the test results does not indicate a great difference in variability between the standard test method and modified test method, particularly in the small mix size (7mm), while the variability increases in the larger mix size (14 mm). The study used a modified procedure of the method in relation to the agitation and timing. By determining an exact time for testing as well as avoiding the agitation component at regular intervals, a higher maximum density can be achieved which in turn translate as less variability in density.

2) The currently used method (Rice method), clearly identifies any issues regarding segregation of the mix. Therefore it is a good guide for identifying problems, particularly when the material is coarse or fine.

5.2 Recommendations

1) The laboratory investigation in this study has identified the necessity to standardise the method of determining bulk density. Of particular importance is the procedure that establishes the measurement of the specimen temperature, which should be 145^{o} C (oven) before compaction. At least one hour in the oven at the suggested temperature is recommended.

2) Based on laboratory testing for the determination of maximum density, the established methodology needs to be revised at the agitation point as it does not contribute in the assistance of the removal of air bubbles. The timing for the procedure should be fixed at an exact 20 minutes.

3) To introduce the recommendations stipulated before, more frequent proficiency and inter-laboratory testing needs to be introduced. This should identify the variability in results and allow for investigation into any issues for continued improvement of testing procedures.

4) It will be necessary to consider an adjustment the current acceptance criteria, as whilst the method gives greater consistency, it is also generating a greater bulk density value, and this will result in a reporting

of lower density values in the field. As historically it has been shown that current compaction standards are achievable, maintaining the current standards for compaction will require considerably greater compactive effort, which may result in stone breakage or lower effective voids leading to instability.

5.2.1 Recommendation for further studies

All procedures in the method can be improved to obtain superior results in the laboratory but there remains the issue of field testing. When testing in the field, the temperature factor is difficult to control due to the exposed conditions. Therefore, uniform compaction levels are harder to achieve. Further studies could investigate the use of a warm mix as alternative to hot mix asphalt. The temperature factor could be control, as the workability of the mix allows for lower temperatures of around 125^{o} C for compaction, and this is not possible with hot mix asphalt.

REFERENCES

Aslab n.d. Asphalt Design Manual – Dense Graded. Bibra Lake: Western Australia.

Asphalt Paving Industry. (2011). A Global Perspective. Second Edition. Global Series 101, from http://www.eapa.org/userfiles/2/ Publications/GL101-2nd-Edition.pdf.

Australian Standard. (1996). “AS 1141. 3.1/ 1996- Method for Sampling and Testing Aggregates”. 2008, from http:// www.saiglobal.com.

Australian Standards. (2005). Hot Mix Asphalt. A guide to good practice. 2008, from http:// www.saiglobal.com.

Australian Standard (2008). “ AS 2891.1.1. – Methods of Sampling and Testing Asphalt Method 1.1: Sampling Loose Asphalt. Australian Standards: pp. 3, 4 and 7.

Australian Standard (2004). “AS 2891.5 – 2004. Australian Standards. Methods for Sampling and Testing Asphalt – Method 5: Determination of Stability and Flow. Marshall Procedure”. 2008, from http://www.saiglobal.com.

Australian Asphalt Pavement Association (2004). National Asphalt Specification. Second Edition: p.5.

Australian Asphalt Pavement Association (2007). Bituminous Surfacing General Principles and Practice – Aggregates: pp. 1 and 2.

Australian Asphalt Pavement Association (2010). Asphalt Compaction Pavement Work Tips: No 12. 2011, from http://www. http://www Aapa.asn.au/technical/pavement-work-tip.html

Austroads (2007). Guide to Pavement Technology Part 4B: Asphalt. Publication No AGPT04B/07. 2011, from http://www.online Publications.austroads.com.au/items/agpt04B-07.

Austroads. (2007). Guide to Pavement Technology Part 4B: Asphalt. Types of Asphalt. Publication No AGPT04B/07: p.10.

ConLaps. (2009). Proficiency Testing Programme. Methods MRWA 731.1, 732.2 AND 733.1. (PT Report 05).

CSR. (2008). Technical Glossary. Retrieved 18th August 2008, from http://www.csr.com.au/technical/glossary.asp

Dickinson, E. J. (1984). Bituminous Roads in Australia. Australian Road Research Board, Vermont South, Victoria.

Hislop, W. and Coree, B. (2000). VMA as a Design Parameter in Hot Mix Asphalt. Retrieved from ntl.bts.gov

Main Roads Western Australia. (2011). “State Road Network”. Retrieved March, 2011, from http://www.mainroads.wa.gov.au/UsingRoads/ Touring WA Maps/Pages/StateRoadsNetworkMaps.aspx

Main Roads Western Australia. (2007). Maximum Density of Asphalt: Rice Method. Test Method WA 732.2. Document No. 71-04-732.2. Retrieved February 2008, from http://www.mainroads.wa.gov.au/ NR/nrwa/frames/Standards/Standardsr.asp?L=/Internet/Standards/ Pavements/.

Main Roads Western Australia. (2010). Stability and Flow of Asphalt: Marshall Method. Test Method WA 731.1. Retrieved June 2010, from http://www.mainroads.wa.gov.au/NR/nrwa/frames/Standards/ Standardsr.asp?L=/Internet/Standards/Pavements/.

Main Roads Western Australia. (2011). Asphalt Mix Design. Document No. 71/06/101. Retrieved May 2011, from http://www.mainroads.wa.gov.au/NR/nrwa/frames/Standards/ Standardsr.asp?L=/Internet/Standards/Pavements

Main Roads Western Australia. (2006). Bulk Density and Void Content of Asphalt. Document No. 71/04/733.1. Retrieved February 2008, from http://www.mainroads.wa.gov.au/NR/nrwa/frames/Standards/ Standardsr.asp?L=/Internet/Standards/Pavements

Main Roads Western Australia. (2011). Bulk Density and Void Content of

Asphalt. Document No. 71/04/733.1. Retrieved June 2011, from http://www.mainroads.wa.gov.au/NR/nrwa/frames/Standards/Standardsr.asp?L=/Internet/Standards/Pavements

Main Roads Western Australia. (2011). Asphalt Wearing Course. Specification 504. Document No. 04/10112. Retrieved September 2011, from http://www.mainroads.wa.gov.au/NR/nrwa/frames/Standards/Standardsr.asp?L=/Internet/Standards/Pavement

Scholz, T.V., Hicks, R. G. and Moulthrop, J. (2002). Preventive Maintenance Versus Reconstruction: Life Cycle Cost Analysis of Various Options. Proceedings, Ninth International Conference on Asphalt Pavement International Society for Asphalt Pavements, Paper 442, Copenhagen, Denmark, August, 2002.

Wallace, H. A. and Martin, J. R. (1967). Asphalt Pavement Engineering. Mc Graw- Hill, United States.

APPENDIX:

APPENDIX A: BULK DENSITY TEST RESULTS

Mix AC 7 /35 sampled and tested: 7/7/2011 **Bulk Density (Method MRWA 733.1)**

First Lot		Non Reheated specimens						Reheated specimens					
Number of Specimens		1	2	3	4	5	6	7	8	9	10	11	12
Temperature °C		139	138	140	136	136	135	140	141	140	141	142	140
Height (mm)		66	65	66	66	64	65	66	66	65	66	65	66
Mass of block in air (g)	m16	1230.12	1231.25	1233.41	1235.54	1230.21	1230.75	1233.23	1233.25	1231.28	1235.28	1234.36	1234.5
Mass of block in water (g)	m17	700.25	696.37	702.65	700.01	691.12	688.32	707.31	704.42	705.98	706.82	705.94	705.89
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**531.46**	**536.49**	**532.36**	**537.14**	**540.71**	**544.06**	**527.50**	**530.42**	**526.88**	**530.05**	**530.01**	**530.20**
(m16 / v4) Marshall density (t/m^3)	md	**2.315**	**2.295**	**2.317**	**2.300**	**2.275**	**2.262**	**2.338**	**2.325**	**2.337**	**2.330**	**2.329**	**2.328**

Second Lot		Non Reheated specimens						Reheated specimens					
Number of Specimens		13	14	15	16	17	18	19	20	21	22	23	24
Temperature °C		140	141	138	137	137	136	140	141	138	140	142	139
Height (mm)		65	66	66	64	66	66	65	65	66	64	66	64
Mass of block in air (g)	m16	1230.09	1234.28	1233.76	1228.32	1231.28	1233.35	1235.36	1234.32	1233.25	1232.24	1234.28	1231.21
Mass of block in water (g)	m17	699	699.56	691.74	686.19	690.52	700.38	707.86	708.38	706.45	706.25	706.28	704.12
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**532.69**	**536.33**	**543.65**	**543.76**	**542.39**	**534.57**	**529.09**	**527.52**	**528.39**	**527.57**	**529.59**	**528.68**
(m16 / v4) Marshall density (t/m^3)	md	**2.309**	**2.301**	**2.269**	**2.259**	**2.270**	**2.307**	**2.335**	**2.340**	**2.334**	**2.336**	**2.331**	**2.329**

Third Lot		Non Reheated specimens						Reheated specimens					
Number of Specimens		25	26	27	28	29	30	31	32	33	34	35	36
Temperature °C		139	139	137	138	136	136	140	139	139	140	140	141
Height (mm)		66	65	66	66	65	66	64	65	65	64	65	64
Mass of block in air (g)	m16	1233.25	1231.52	1234.33	1234.28	1233.83	1235.61	1231.28	1233.64	1234.98	1231.85	1232.58	1230.07
Mass of block in water (g)	m17	701.83	703.72	693.77	692.01	691.02	689.73	706.73	706.35	705.76	707.33	707.06	703.41
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**533.02**	**529.39**	**542.19**	**543.90**	**544.44**	**547.52**	**526.13**	**528.88**	**530.81**	**526.10**	**527.10**	**528.24**
(m16 / v4) Marshall density (t/m^3)	md	**2.314**	**2.326**	**2.277**	**2.269**	**2.266**	**2.257**	**2.340**	**2.333**	**2.327**	**2.341**	**2.338**	**2.329**

Mix AC 10/50 sampled and tested: 4/3/2011 **Bulk Density (Method MRWA 733.1)**

First Lot		**Non Reheated specimens**						**Reheated specimens**					
Number of Specimens		1	2	3	4	5	6	7	8	9	10	11	12
Temperature ^oC		137	138	142	137	136	138	141	142	140	141	139	140
Height (mm)		65	65	66	66	65	66	64	64	65	66	64	65
Mass of block in air (g)	m16	1233.24	1235.31	1234.25	1233.25	1234.31	1235.65	1233.48	1235.21	1234.92	1231.51	1233.88	1231.25
Mass of block in water (g)	m17	691.25	698.34	702.32	698.86	706.18	698.68	709.01	708.87	709.1	707.63	706.51	706.71
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**543.62**	**538.59**	**533.53**	**536.00**	**529.72**	**538.59**	**526.05**	**527.92**	**527.40**	**525.46**	**528.96**	**526.12**
(m16 / v4) Marshall density (t/m^3)	md	**2.269**	**2.294**	**2.313**	**2.301**	**2.330**	**2.294**	**2.345**	**2.340**	**2.342**	**2.344**	**2.333**	**2.340**

Second Lot		**Non Reheated specimens**						**Reheated specimens**					
Number of Specimens		13	14	15	16	17	18	19	20	21	22	23	24
Temperature ^oC		139	140	138	135	137	138	141	140	139	140	141	140
Height (mm)		65	66	66	66	65	66	65	64	65	65	65	65
Mass of block in air (g)	m16	1234.64	1230.28	1234.58	1234.28	1231.28	1232.24	1231.78	1230.89	1233.52	1234.1	1234.98	1232.28
Mass of block in water (g)	m17	703.51	696.67	697.84	700.52	698.85	700.45	709	707.29	708.05	709.84	711.28	706.71
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**532.73**	**535.22**	**538.36**	**535.37**	**534.03**	**533.39**	**524.35**	**525.18**	**527.05**	**525.84**	**525.28**	**527.15**
(m16 / v4) Marshall density (t/m^3)	md	**2.318**	**2.299**	**2.293**	**2.305**	**2.306**	**2.310**	**2.349**	**2.344**	**2.340**	**2.347**	**2.351**	**2.338**

Third Lot		**Non Reheated specimens**						**Reheated specimens**					
Number of Specimens		25	26	27	28	29	30	31	32	33	34	35	36
Temperature ^oC		138	140	139	137	136	136	139	139	139	140	140	140
Height (mm)		66	66	65	66	66	65	65	65	66	65	64	64
Mass of block in air (g)	m16	1235.36	1233.75	1234.31	1233.21	1236.28	1231.28	1234.18	1231.12	1234.04	1233.25	1234.28	1231.21
Mass of block in water (g)	m17	702.03	695.12	699.68	698.85	702.68	706.59	708.05	708.08	710.1	706.05	707.62	705.58
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**534.93**	**540.25**	**536.24**	**535.97**	**535.21**	**526.27**	**527.71**	**524.61**	**525.52**	**528.79**	**528.24**	**527.21**
(m16 / v4) Marshall density (t/m^3)	md	**2.309**	**2.284**	**2.302**	**2.301**	**2.310**	**2.340**	**2.339**	**2.347**	**2.348**	**2.332**	**2.337**	**2.335**

Mix AC 14/75 sampled and tested: 11/5/2011 **Bulk Density (Method MRWA 733.1)**

First Lot		Non Reheated specimens						Reheated specimens					
Number of Specimens		1	2	3	4	5	6	7	8	9	10	11	12
Temperature ^{o}C		142	141	140	141	137	139	141	142	140	141	139	140
Height (mm)		64	65	64	64	63	64	65	65	64	65	65	65
Mass of block in air (g)	m16	1230.3	1230.25	1233.25	1231.08	1229.55	1232.12	1233.77	1234.28	1232.78	1232.84	1234.72	1231.82
Mass of block in water (g)	m17	712.35	710.29	711.25	711.39	709.38	711.19	713.64	713.43	716	714.18	715.05	713.87
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**519.51**	**521.52**	**523.57**	**521.25**	**521.74**	**522.50**	**521.70**	**522.42**	**518.34**	**520.22**	**521.23**	**519.51**
(m16 / v4) Marshall density (t/m^3)	md	**2.368**	**2.359**	**2.355**	**2.362**	**2.357**	**2.358**	**2.365**	**2.363**	**2.378**	**2.370**	**2.369**	**2.371**

Second Lot		Non Reheated specimens						Reheated specimens					
Number of Specimens		13	14	15	16	17	18	19	20	21	22	23	24
Temperature ^{o}C		139	140	137	138	139	139	141	140	139	142	143	138
Height (mm)		65	64	65	66	65	65	64	64	65	64	65	64
Mass of block in air (g)	m16	1233.65	1233.26	1234.87	1231.24	1234.82	1233.98	1234.28	1230.25	1233.65	1230.75	1235.64	1230.07
Mass of block in water (g)	m17	714.55	713.44	713.99	710.34	714.56	714.2	714.18	713.25	712.81	712.77	716.47	711.71
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**520.66**	**521.38**	**522.45**	**522.47**	**521.83**	**521.34**	**521.66**	**518.56**	**522.41**	**519.54**	**520.73**	**519.92**
(m16 / v4) Marshall density (t/m^3)	md	**2.369**	**2.365**	**2.364**	**2.357**	**2.366**	**2.367**	**2.366**	**2.372**	**2.361**	**2.369**	**2.373**	**2.366**

Third Lot		Non Reheated specimens						Reheated specimens					
Number of Specimens		25	26	27	28	29	30	31	32	33	34	35	36
Temperature ^{o}C		137	142	140	139	139	137	139	140	140	141	141	139
Height (mm)		64	64	65	65	65	64	64	64	65	64	65	64
Mass of block in air (g)	m16	1231.34	1230.28	1234.65	1231.87	1234.31	1229.31	1231.29	1233.26	1232.22	1230.71	1233.65	1231.28
Mass of block in water (g)	m17	711.2	714.55	714.72	714.32	714.33	709.44	714.24	716	711.75	712.84	714.85	712.28
((m16 - m17) / 0.997) Volume of block (cm^3)	v4	**521.71**	**517.28**	**521.49**	**519.11**	**521.54**	**521.43**	**518.61**	**518.82**	**522.04**	**519.43**	**520.36**	**520.56**
(m16 / v4) Marshall density (t/m^3)	md	**2.360**	**2.378**	**2.368**	**2.373**	**2.367**	**2.358**	**2.374**	**2.377**	**2.360**	**2.369**	**2.371**	**2.365**

APPENDIX:

APPENDIX B: MAXIMUM DENSITY TEST RESULTS

Mix AC 7 /35 sampled and tested: 28/4/2011 **Maximum Density (Rice Method MRWA 732.2)**

First Lot			STANDARDS					Non STANDARD				
Number of Specimens			1	2	3	4	5	6	7	8	8	10
Sample Mass (g)		m12	1120.32	1129.30	1125.32	1123.28	1124.38	1126.54	1125.69	1127.62	1126.68	1123.55
Mass flask & sample in water (g)		m13	1381.23	1385.43	1383.88	1383.65	1381.84	1385.47	1385.20	1386.78	1386.00	1383.74
Mass flask in water (g)		m14	729.69	729.69	729.69	729.69	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14)	Mass of sample in water (g)	m15	**651.54**	**655.74**	**654.19**	**653.96**	**652.67**	**656.30**	**656.03**	**657.61**	**656.83**	**654.57**
(m12 - m15 /0.997)	Sample volume (cm^3)	v3	**470.19**	**474.98**	**472.55**	**470.73**	**473.13**	**471.65**	**471.07**	**471.42**	**471.26**	**470.39**
(m12 / v3)	Maximum density t/m^3	rd	**2.383**	**2.378**	**2.381**	**2.386**	**2.376**	**2.388**	**2.390**	**2.392**	**2.391**	**2.389**

Second Lot			STANDARDS					Non STANDARD				
Number of Specimens			11	12	13	14	15	16	17	18	19	20
Sample Mass (g)		m12	1125.32	1126.84	1121.25	1124.22	1126.87	1129.64	1126.34	1123.25	1126.31	1124.37
Mass flask & sample in water (g)		m13	1383.51	1385.28	1381.42	1383.15	1385.47	1387.65	1384.99	1382.82	1384.07	1384.17
Mass flask in water (g)		m14	729.17	729.69	729.69	729.69	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14)	Mass of sample in water (g)	m15	**654.34**	**655.59**	**651.73**	**653.46**	**656.30**	**658.48**	**655.82**	**653.65**	**654.90**	**655.00**
(m12 - m15 /0.997)	Sample volume (cm^3)	v3	**472.40**	**472.67**	**470.93**	**472.18**	**471.99**	**472.58**	**471.94**	**471.01**	**472.83**	**470.78**
(m12 / v3)	Maximum density t/m^3	rd	**2.382**	**2.384**	**2.381**	**2.381**	**2.388**	**2.390**	**2.387**	**2.385**	**2.382**	**2.388**

Third Lot			STANDARDS					Non STANDARD				
Number of Specimens			21	22	23	24	25	26	27	28	29	30
Sample Mass (g)		m12	1126.37	1124.35	1123.21	1125.26	1124.02	1127.44	1126.32	1123.37	1125.87	1124.56
Mass flask & sample in water (g)		m13	1383.25	1382.75	1381.48	1384.51	1381.81	1386.54	1385.54	1384.00	1385.00	1384.77
Mass flask in water (g)		m14	729.17	729.69	729.69	729.69	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14)	Mass of sample in water (g)	m15	**654.08**	**653.06**	**651.79**	**654.82**	**652.64**	**657.37**	**656.37**	**654.83**	**655.83**	**655.60**
(m12 - m15 /0.997)	Sample volume (cm^3)	v3	**473.71**	**472.71**	**472.84**	**471.86**	**472.80**	**471.48**	**471.36**	**469.95**	**471.45**	**470.37**
(m12 / v3)	Maximum density t/m^3	rd	**2.378**	**2.379**	**2.375**	**2.385**	**2.377**	**2.391**	**2.389**	**2.390**	**2.388**	**2.391**

Mix AC 10/50 sampled and tested: 14/4/2011

Maximum Density (Rice Method MRWA 732.2)

First Lot		STANDARDS					Non STANDARD				
Number of Specimens		1	2	3	4	5	6	7	8	8	10
Sample Mass (g)	m12	1230.21	1231.78	1233.12	1231.17	1234.52	1230.5	1231.21	1234.27	1231.26	1233.73
Mass flask & sample in water (g)	m13	1458.78	1460.61	1459.86	1460.00	1461.09	1461.45	1461.54	1462.97	1460.59	1463.20
Mass flask in water (g)	m14	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14) Mass of sample in water (g)	m15	**729.61**	**731.44**	**730.69**	**730.83**	**731.92**	**732.28**	**732.37**	**733.80**	**731.42**	**734.03**
(m12 - m15 /0.997) Sample volume (cm^3)	v3	**502.11**	**501.85**	**503.94**	**501.85**	**504.11**	**499.72**	**500.34**	**501.98**	**501.34**	**501.20**
(m12 / v3) Maximum density t/m^3	rd	**2.450**	**2.455**	**2.447**	**2.453**	**2.449**	**2.462**	**2.461**	**2.459**	**2.456**	**2.462**

Second Lot		STANDARDS					Non STANDARD				
Number of Specimens		11	12	13	14	15	16	17	18	19	20
Sample Mass (g)	m12	1233.01	1230.19	1231.58	1234.73	1231.61	1234.52	1232.58	1236.64	1234.22	1233.31
Mass flask & sample in water (g)	m13	1460.63	1459.32	1459.00	1459.87	1457.32	1463.51	1462.12	1464.86	1463.78	1463.67
Mass flask in water (g)	m14	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14) Mass of sample in water (g)	m15	**731.46**	**730.15**	**729.83**	**730.70**	**728.15**	**734.34**	**732.95**	**735.69**	**734.61**	**734.50**
(m12 - m15 /0.997) Sample volume (cm^3)	v3	**503.06**	**501.54**	**503.26**	**505.55**	**504.97**	**501.69**	**501.13**	**502.46**	**501.11**	**500.31**
(m12 / v3) Maximum density t/m^3	rd	**2.451**	**2.453**	**2.447**	**2.442**	**2.439**	**2.461**	**2.460**	**2.461**	**2.463**	**2.465**

Third Lot		STANDARDS					Non STANDARD				
Number of Specimens		21	22	23	24	25	26	27	28	29	30
Sample Mass (g)	m12	1234.56	1229.89	1232.54	1231.17	1233.54	1231.28	1230.29	1232.52	1230.09	1235.84
Mass flask & sample in water (g)	m13	1460.51	1458.00	1460.12	1458.00	1460.25	1462.00	1462.02	1461.62	1460.73	1463.65
Mass flask in water (g)	m14	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14) Mass of sample in water (g)	m15	**731.34**	**728.83**	**730.95**	**728.83**	**731.08**	**732.83**	**732.85**	**732.45**	**731.56**	**734.48**
(m12 - m15 /0.997) Sample volume (cm^3)	v3	**504.73**	**502.57**	**503.10**	**503.85**	**503.97**	**499.95**	**498.94**	**501.57**	**500.03**	**502.87**
(m12 / v3) Maximum density t/m^3	rd	**2.446**	**2.447**	**2.450**	**2.444**	**2.448**	**2.463**	**2.466**	**2.457**	**2.460**	**2.458**

Mix AC 14/75 sampled and tested: 12/5/20111 **Maximum Density (Rice Method MRWA 732.2)**

First Lot		STANDARDS					Non STANDARD				
Number of Specimens		1	2	3	4	5	6	7	8	8	10
Sample Mass (g)	m12	1510.12	1512.24	1511.28	1508.85	1510.23	1513.34	1509.24	1510.28	1508.25	1501.26
Mass flask & sample in water (g)	m13	1629.82	1632.39	1633.00	1630.28	1632.00	1637.34	1636.05	1635.89	1635.76	1630.01
Mass flask in water (g)	m14	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14) Mass of sample in water (g)	m15	**900.65**	**903.22**	**903.83**	**901.11**	**902.83**	**908.17**	**906.88**	**906.72**	**906.59**	**900.84**
(m12 - m15 /0.997) Sample volume (cm^3)	v3	**611.30**	**610.85**	**609.28**	**609.57**	**609.23**	**606.99**	**604.17**	**605.38**	**603.47**	**602.23**
(m12 / v3) Maximum density t/m^3	rd	**2.470**	**2.476**	**2.480**	**2.475**	**2.479**	**2.493**	**2.498**	**2.495**	**2.499**	**2.493**

Second Lot		STANDARDS					Non STANDARD				
Number of Specimens		11	12	13	14	15	16	17	18	19	20
Sample Mass (g)	m12	1505.15	1508.54	1510.74	1512.13	1511.73	1518.31	1514.43	1517.32	1515.12	1506.61
Mass flask & sample in water (g)	m13	1627.01	1631.28	1633.00	1633.05	1630.51	1639.87	1637.09	1639.79	1639.58	1633.75
Mass flask in water (g)	m14	729.17	729.69	729.69	729.69	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14) Mass of sample in water (g)	m15	**897.84**	**901.59**	**903.31**	**903.36**	**901.34**	**910.70**	**907.92**	**910.62**	**910.41**	**904.58**
(m12 - m15 /0.997) Sample volume (cm^3)	v3	**609.14**	**608.78**	**609.26**	**610.60**	**612.23**	**609.44**	**608.34**	**608.53**	**606.53**	**603.84**
(m12 / v3) Maximum density t/m^3	rd	**2.471**	**2.478**	**2.480**	**2.476**	**2.469**	**2.491**	**2.489**	**2.493**	**2.498**	**2.495**

Third Lot		STANDARDS					Non STANDARD				
Number of Specimens		21	22	23	24	25	26	27	28	29	30
Sample Mass (g)	m12	1516.45	1512.34	1510.24	1517.35	1512.27	1514.24	1505.74	1509.1	1520.24	1515.12
Mass flask & sample in water (g)	m13	1634.32	1631.09	1630.00	1635.31	1633.31	1637.05	1632.73	1633.52	1641.35	1639.00
Mass flask in water (g)	m14	729.17	729.69	729.69	729.69	729.17	729.17	729.17	729.17	729.17	729.17
(m13 - m14) Mass of sample in water (g)	m15	**905.15**	**901.40**	**900.31**	**905.62**	**904.14**	**907.88**	**903.56**	**904.35**	**912.18**	**909.83**
(m12 - m15 /0.997) Sample volume (cm^3)	v3	**613.14**	**612.78**	**611.77**	**613.57**	**609.96**	**608.18**	**603.99**	**606.57**	**609.89**	**607.11**
(m12 / v3) Maximum density t/m^3	rd	**2.473**	**2.468**	**2.469**	**2.473**	**2.479**	**2.490**	**2.493**	**2.488**	**2.493**	**2.496**

APPENDIX

APPENDIX C: MODIFIED BULK DENSITY METHOD

Modified Bulk Density Method

a) For compaction, the mould (base and extension collar) was placed in the oven for at least one hour.

b) Mould was removed from the oven and a paper disc was placed into the mould.

c) A single test portion was placed into the mould (normally a mass of between 1200g and 1250g is required). A paper disc was then positioned on the surface of the material in the mould and a thermometer was inserted into the centre of the mould.

d) **The temperature of the test portion was recorded. The mould and test portion were placed in the oven for 1 hour at a temperature of 145^{o}C. After the hour the specimen temperature was registered and it was noticed that the temperature was even throughout the specimen.**

e) The thermometer was removed. The mould and test portion were placed into position on the compaction pedestal. . The specimen is compacted according to mix on one side. The mould then was inverted and the same number of blows was applied to the other end of the test portion. Note that the number of blows varied according to the mix specifications.

f) The mould was given an identification number.

g) The mould and test specimen were left to cool down.

h) The specimen is removed from the mould when it is cool and it is ready for testing.

APPENDIX

APPENDIX D: MODIFIED RICE METHOD

Maximum Density- Modified Rice Method

1. A test sample was obtained in accordance with Test method MRWA 701.12.

2. The particles of the test portion were manually separate so that no aggregations of fine particles were larger than approximately 5 mm. Using sample division obtain a test portion from the test sample.

3. Mass was recorded to the nearest 0.1g and the flask was immersed in water (M_1) at 25 $\pm$ 1.0^o C.

4. The flask was partially filled with water from the bath to cover the sample. Approximately 2ml of detergent was added to the water.

5. The test portion was placed into the flask and the mass recorded to the nearest 0.1g (M_2).

6. The flask was stoppered and connected to a vacuum pump to remove the entrapped air of at least 90kPa, for 20 minutes.

7. The flask was not agitated periodically but only after 20 minutes exactly.

8. The flask was disconnected from the vacuum and submerged into a temperature controlled water bath (ensuring the sample was covered with water at all times to avoid introducing air).

9. The mass of the flask was recorded to the nearest 0.1g (M_3) and the test portion put underwater.

10. Determination of the specimen’s maximum density was carried out to the nearest 0.001 t/m^3.